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Controlled Ecological Life Support System

Biological Problems

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Proceedings of two NASA workshops
held at the University of New Hampshire
Durham, New Hampshire
October and December 1979

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Controlled Ecological Life Support System

Biological Problems

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Contents

PREFACE v

1. INTRODUCTION 1
   - Purpose and Scope 1
   - Background 1

2. RLSR PROGRAM EXPERIMENTAL DESIGN STRATEGY 3
   - Overview 3
   - Exogenous Control 5
   - Endogenous Control 7
   - Program Synthesis 10

3. BIOTIC PRODUCTION 11
   - Overview 11
   - Gnotobiotic Production in an Exogenously Controlled System 12
   - Suggested Experiments for Biotic Production 12

4. WASTE TREATMENT AND DECOMPOSITION 15
   - Overview 15
   - Inputs vs. Outputs 16
     - Outputs 16
       - Inorganic Compounds 17
       - Salts 17
       - Trace Metals 17
       - Gaseous Effluents 18
   - Modeling 18
   - Treatment Processes—Physiochemical 19
     - Overview 19

Combustion 19
Research Issues 21
Research Priorities 22
Wet Oxidation 22
Research Issues 23
Treatment Processes—Biological 24
Overview 24
Activated Sludge 24
Composting 26
Research Issues 27
Aqueous Biotic Oxidation 27
Semisolid Biotic Oxidation (Composting) 29
Research Priorities 29
Aqueous Systems 29
Semisolid Systems 29

REFERENCES 31

PARTICIPANTS AND AUTHORS 33

PREFACE

Here is summarized the results of two workshops held in October and December 1979, at the New England Center for Continuing Education, University of New Hampshire, Durham, New Hampshire. The purpose of the workshops was to identify particular biological issues associated with research on Controlled Ecological Life Support Systems (CELSS). The results of the workshops are intended to contribute to the development of a comprehensive program plan for the National Aeronautics and Space Administration's (NASA's) Regenerative Life Support System Research (RLSR) program.

The workshop discussions were directed toward elemental cycles and the biological factors that affect the transformations of nutrients into food, food material into waste, and waste into nutrients. To focus on the biological issues, the discussion assumed that food production would be by biological means (thus excluding chemical synthesis), that energy would not be a limiting factor, and that engineering capacity for controlling environmental conditions (e.g., temperature, humidity, atmospheric composition, and leak rate) would be adequate.

In previous studies and workshops, the rationale for investigating closed and partially closed life support systems, as well as the necessity for research on biological issues, was outlined. Broad in scope, these previous efforts have attempted to provide a reasonably comprehensive context for viewing research needs, and they enhanced the possibility of an expanded, although still limited, program of research.

Effective use of limited resources requires that critical research problems be identified and that a corresponding strategy of experimental and theoretical investigations be developed. The workshops reviewed here were two of several sponsored by NASA to fulfill these requirements. The results will be used in the comprehensive program planning.

The report summarizes an experimental design strategy recommended by the first workshop, identifies research issues and approaches to biotic food production, and examines the issues associated with selecting processes for waste processing and decomposition.

The recommended experimental program includes two distinct approaches to establishing and controlling a regenerated life support system: (1) exogenous control, which is heavily dependent on human manipulations of system functions, with initial emphasis on the engineering approach; and (2) endogenous control, which is heavily dependent on internal control mechanisms, with emphasis on the biological control inherent in natural ecosystems.

The recommended strategy provides for simple regenerative experiments for each of the two approaches, monitoring two major material flow vectors: the *maintenance influent*

vector (MIV) and the *waste effluent vector* (WEV). These vectors must balance eventually, with the regenerative processes converting the waste (WEV) into the nutrients and other materials (MIV) required to sustain productive life. However, as the experimental program is started, imbalances in these flows ("cheating vectors") are permitted (even encouraged) in order to extend the longevity of the experimental systems. Identifying and monitoring these cheating vectors are necessary to gain an understanding of regenerative system requirements.

As the program proceeds from simple experiments (e.g., maintenance of single plants) to more complex experiments (e.g., maintenance of multiple species and an MIV developed from a WEV), information should be exchanged between the two approaches. Each strategy may be modified by incorporating the most reliable and efficient features of its counterpart to improve the control designs. As the parallel experiments proceed toward increasing complexity, five rules of convergence provide guidance for modifying the experimental control strategies:

1. Cheating vectors in the wet laboratory cannot be allowed to increase in magnitude.
2. The degree of endogenous control in the biological approach should not be allowed to increase.
3. Information and technology should flow freely between the two designs and within design approaches.
4. Special events and "failures" should be purposefully planned. The consequences of plants and animals dying, excess production, and contamination, as well as the subsequent reestablishment of components should be tested experimentally.
5. The overall goal of research is to design a system that minimizes the number of human manipulations needed to maintain system stability. The two different experimental approaches will arrive at this number from two different directions. The approach that depends on exogenous control will have to reduce the initial degree of human manipulation, whereas the approach that depends on endogenous control will have to increase the initial degree of human control.

The objectives of the recommended experimental program may be summarized as follows:

1. To determine the necessary monitoring points.
2. To determine the composition of the WEV and MIV.
3. To reduce the cheating vectors to processing vectors.
4. To improve the efficiency of the engineering approach of complete combustion and resynthesis, and of the biological approach of microbially mediated decomposition.

Research of the biotic production of food should proceed and converge from two distinct theoretical paradigms for growing plants:

1. Gnotobiotic—in which plants are grown in an environment that is biologically defined.

2. Conventional—in which the normal complement of plant microorganisms is used to reduce the need for exogenous controls.

These paradigms parallel the overall experimental strategy: The gnotobiotic approach is consistent with the experimental strategy that stresses exogenous controls, and the conventional approach is consistent with the experimental strategy that stresses endogenous controls. Experiments in biotic food production could follow the two recommended experimental approaches and be designed to accomplish the following objectives:

1. Determine the health and productivity of plants contaminated with human microorganisms and grown in association with differing levels of natural microflora.

2. Determine the health and productivity of plants that are grown under the above conditions in which the MIV is varied so that any changes caused by different MIVs, which would result from changes in human diet or process technologies, can be determined.

3. Identify potential macroindicators of system performance, such as shifts in microbial populations, that might forecast trouble.

4. Identify opportunities for design guidelines arising from potential system interactions, such as the feasibility of a silicon-free growth environment to avoid the formation of recalcitrant compounds by the waste-processing function.

5. Identify required and detrimental plant gas interactions, particularly the response of plants to gases that include signal molecules.

A research program for waste processing should emphasize investigations of several techniques. Two overall processes, each with two generic approaches, seem to warrant study: (1) physiochemical processes, comprising combustion and wet oxidation; and (2) biological processes, comprising activated sludge and composting.

These overall processes parallel the overall experimental strategy. The physiochemical processes are consistent with the experimental strategy that stresses exogenous control; the biological processes are consistent with the experimental strategy that stresses endogenous control. Each of these approaches has potential advantages, but considerable research is necessary to resolve important unknowns. The report outlines priorities for research. The priorities involve issues related to the fate of inorganic compounds and trace elements (especially metals) and to the separation of salt compounds. Issues related particularly to biological approaches include the following:

1. What species of microbial flora are likely to develop into dominant populations, and how sensitive are they to changes in inputs?

2. How will refractory compounds, residues, and mixing in environments of less than 1 g be handled?

Both the physiochemical and biological approaches require systematic studies aimed at characterization of the process outputs as functions of inputs and process parameters such as temperature, pressure, and residence time. Related modeling research is recommended in order to (1) identify the relations between approaches for waste processing and approaches for other regenerative life support functions, and (2) identify potential combinations of waste processing approaches whose overall performance is superior to that of the individual approaches.

1. INTRODUCTION

Purpose and Scope

Here is summarized the results of two workshops held in October and December 1979, at the New England Center for Continuing Education, University of New Hampshire, Durham, New Hampshire. The purpose of the workshops was to identify particular biological issues associated with research on Controlled Ecological Life Support Systems (CELSS). The results of the workshops are intended to contribute to the development of a comprehensive program plan for the National Aeronautics and Space Administration's (NASA's) Regenerative Life Support System Research (RLSR) program.

The general processes and controls associated with two distinct experimental paradigms are examined in Section 2. Subsequent sections explore specific areas for research related to biotic production (food production [Sec. 3]) and biotic decomposition (waste management) (Sec. 4). These two fundamental components of the RLSR Program were examined separately at the two workshops. Because participants of both workshops felt that these basic issues merited detailed attention early in the research program, issues of human nutrition, environmental requirements, and overall system management were not considered in these sessions.

The workshop discussions were directed toward elemental cycles and the biological factors that affect the transformations of nutrients into food, of food material into waste, and of waste into nutrients. To focus on biological issues, the discussion assumed that (1) food production would be by biological means (thus excluding chemical synthesis), (2) energy would not be a limiting factor, and (3) engineering capacity for controlling environmental conditions (e.g., temperature, humidity, atmospheric composition and leak rate) would be adequate.

Background

Previous studies and workshops have outlined the rationale for investigating closed and partially closed life-support systems as well as the necessity for research on biological issues (Tibbitts and Alford, 1980; Mason and Carden, 1979; MacElroy and Averner, 1978; Taub, 1974). Of broad scope, these earlier efforts were attempts to provide a reasonably comprehensive context for viewing research needs, and they have increased the possibility of an expanded, although still limited, program of research.

Effective use of limited resources requires that critical research problems be identified and that a corresponding strategy of experimental and theoretical investigations be developed. The workshops reported here were two of several sponsored by NASA to fulfill these requirements. The results will be used in the comprehensive program planning.

Section 2 summarizes an experimental design strategy recommended by the first workshop. Section 3 reviews the research considerations and issues associated with biotic food production. Section 4 identifies and examines fundamental issues associated with selecting processes for waste treatment and decomposition, outlines four processes that should be studied (combustion, wet oxidation, semisolid biological decomposition, and aqueous biological decomposition), and summarizes the needed research on these processes and the waste-processing function. The list of references cannot be considered a comprehensive treatment of the fields involved; yet the references are an important and characteristic subset of the relevant literature.

2. RLSR PROGRAM EXPERIMENTAL DESIGN STRATEGY

Overview

The purpose of a Regenerative Life Support Research (RLSR) program would be to broaden our understanding of the processes and controls of systems, including regenerative life-support systems, and thereby improve our ability to reproduce them. To achieve this goal, an RLSR experimental program could begin with polar control strategies: exogenous control, which depends heavily on human manipulations of the system, and endogenous control, which relies heavily on the internal mechanisms of natural ecosystems (fig 1). These two strategies imply two different approaches—engineering and biological—toward establishing regenerative systems. Each approach uses a different set of options for the major system functions, and thereby increases our knowledge of a wide range of mechanisms available for use in a Controlled Ecological Life Support System (CELSS). In addition, these strategies and their concurrent approaches and options can be used to guide research and to manage the experimental program.

An exogenous control strategy maximizes the ability of humans to direct the system through physical manipulation. It substitutes engineering processes and controls in a regenerative system for their biological counterparts. The engineered processes and controls simplify the mechanisms for regeneration and, in doing so, may permit us to understand more fully the remaining biological mechanisms. As our understanding grows, we are better able to identify the points of control, which helps us increase the effectiveness of exogenous controls. By replacing biological processes with engineered processes, researchers could test the limits of such substitutions and learn the tolerance of an ecosystem for displacement of biological mechanisms by physical chemical processes.

The other control strategy, endogenous control, seeks initially to minimize human involvement in the system. Instead, stability of the life-support system depends on the internal control mechanisms that operate within natural ecosystems. To preserve these internal mechanisms, the biological component of natural systems would have to be kept intact, as much as possible, in the systems used for experimentation. Nevertheless, humans would retain some control over the experimental system through a restricted set of exogenous manipulations (e.g., changing the light, temperature, and pH). Research would be designed to improve our understanding of the endogenous control mechanisms and would focus on the system behavior that results from human manipulation of the vast, poorly understood array of endogenous control mechanisms.

The capacity to construct an operational CELSS unit could serve as a conceptual goal to guide the RLSR program. This report outlines a research program involving both endogenous and exogenous control systems. The program stresses the identification and

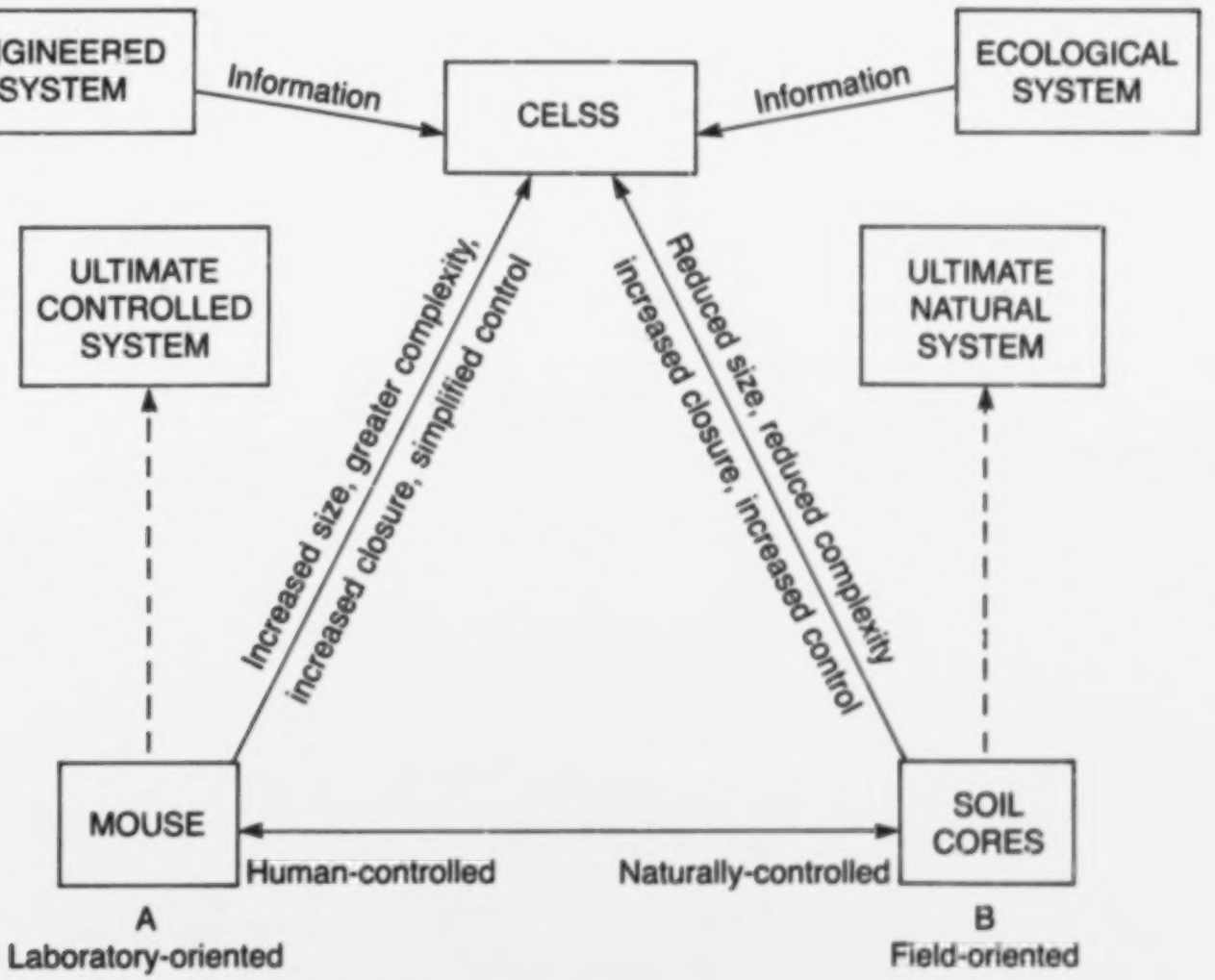

Figure 1. Experimental design for regenerative life-support research program.

examination of various processes (and their control mechanisms) that could be used in a CELSS. Progress toward the theoretical ability to construct an operational CELSS unit, coupled with this dual-faceted approach, would provide a pool of well-understood life-support processes from which NASA could select those to be used in CELSS.

Each of the two experimental approaches starts simply; complexity could increase as individual experiments meet predetermined system criteria and goals. Throughout the RLSR program, information should be exchanged between both approaches and all subprograms. The different experimental systems should make more stable operational systems possible, as the more reliable and efficient processes and controls of one system are built into the other. Eventually, the two systems and their hybrids should merge at a level of scientific and technical understanding that could provide the foundation for the construction of one or more kinds of ground-testable CELSS units.

Exogenous Control

In a system that maximizes exogenous control, humans manage a large number of the processes and controls normally carried out by the natural ecosystem. The degree of human control could be increased by replacing—wherever such substitution appears useful—biological processes and controls with their engineering equivalents. Endogenous controls in plants and people that relate to their physiology, dynamics of growth, and development will, of course, remain.

Figure 2 is a flow diagram of the exogenously controlled system. The maintenance influent vector (MIV) and the waste effluent vector (WEV) are the key monitoring points. The MIV is made up of the solid, liquid, and gaseous compounds necessary for a hospitable environment (e.g., food, drink, and air) and the WEV is made up of the gaseous, liquid, and solid wastes produced by the living organisms. These two vectors must be monitored so that humans can maintain a hospitable system within the environment.

One of the basic requirements of a final CELSS unit is that flow to the outside be reduced to a minimum and closely tracked; almost all materials must be carefully monitored and recycled. In addition, the closure requirement could serve as a useful scientific construct for understanding regenerative systems. The difficult process in this closure would be the conversion of the WEV into the MIV. Humans could maximize their exogenous control over the closure of the cycling loop by processing the WEV in a wet laboratory. The wet laboratory is a combination of physical and chemical processes that converts wastes into usable forms. The particular processes or reactions used in the wet laboratory depend on the makeup of the WEV and on the desired chemical rearrangement. Thus, to design and choose these processes and reactions, the molecular composition and oxidation states of the important biological elements (C, N, P, S, and so on) must be known. These conversions will, in general, decompose large organic molecules into inorganic compounds, with the biologically important elements in their highest oxidation states (see Section 4).

Many wet laboratory processes or reactions require nonrenewable reagents, and as new substances are discovered in the WEV, new reactions must be added to the laboratory to treat them. This use of nonrenewable reagents and the addition of new reactions violates a second requirement of the final design for constructing a CELSS, that of maintaining mass balance. Although such violations of mass balance, which are termed cheating vectors, are allowed in the initial phase of experimentation (for the purpose of ex-

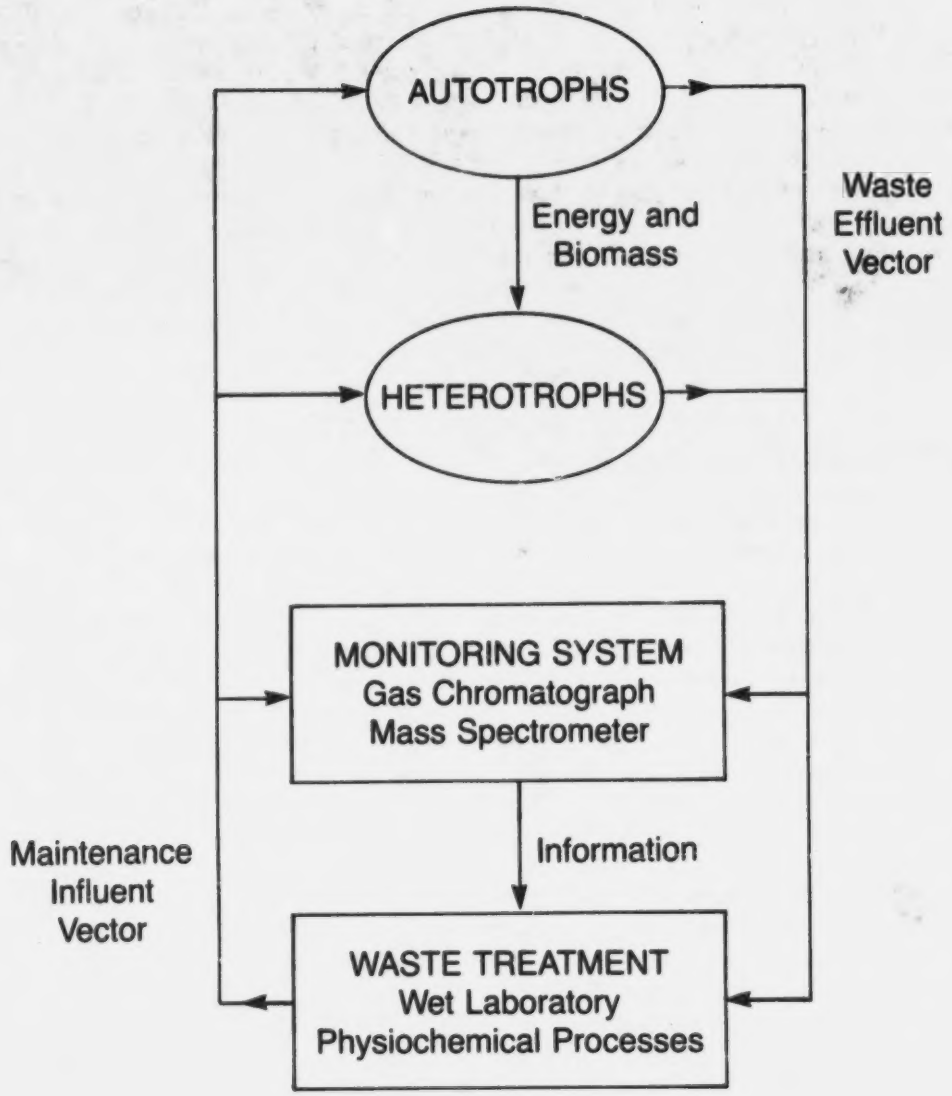

Figure 2. Exogenous control.

tending the longevity of experimental systems), their use must be carefully identified and noted. A rule necessary for meeting sucessive design criteria—as well as for measuring our understanding of regenerative systems per se—stipulates a gradual reduction in the number and magnitude of cheating vectors.

Initially, all of the components of the MIV and WEV will be monitored very closely. The exogenously controlled system would use instruments, such as chromatographs and mass spectrometers, to monitor the molecular composition and oxidation states of the MIV and WEV. Mass spectrometer or gas chromatograph fingerprints of a healthy CELSS unit could be stored in a computer, and monitoring could consist of comparing actual conditions to these prints. Identification and evaluation of fingerprints, as well as the development of successful monitoring strategies, will be an important research area.

Although the exogenously controlled system is initially designed to increase human control, the overall goal of this approach and that of the entire experimental program is to minimize the degree of human manipulation needed for system stability, because monitoring to effect exogenous control is a perturbation of the system. Therefore, reducing the scope of any monitoring is an important goal of the experimental program. One of the criteria for successive monitoring systems should be a gradual lessening of the perturbations. This reduction could be accomplished by limiting monitoring to the vector components that are essential to system function. These critical components could be identified through experimental work done on small systems, especially the partial enclosure experiments to be undertaken within the exogenously controlled system.

Actual experimentation in the exogenously controlled system could start simply. An initial closed-system experiment might consist of one or two species of hydroponic plants and possibly an animal (e.g., a lizard) in a glove box. The animal would be kept in a metabolism cage so that its solid and liquid wastes could be collected. The wastes of the plants and the animals would be collected and regenerated into a MIV in the wet laboratory. Respiratory gases would be regenerated through the photosynthetic cycle. Criteria for determining the success of an enclosure, such as the longevity of the system or the elimination of a cheating vector, should be established at the outset.

As experimental criteria are met, the complexity of the experimental system should be increased (e.g., modularizing glove boxes by linking them together and adding more species and gradually eliminating cheating vectors). Phytotrons may be especially useful facilities for advanced enclosure experiments (see Proceedings 1978; Downs et al., 1972; Kramer et al., 1970).

Endogenous Control

An endogenous system maximizes naturally occurring control mechanisms; the biological component carries out all life-support and recycling functions. In such an ecosystem, with its emphasis on unaltered biological mechanisms, the initial level of human manipulation would be minimized. The flow diagram of the endogenously controlled system is shown in figure 3.

Again, the dominant monitoring points are the MIV and WEV. This endogenous approach maximizes the system's biological component, which requires and creates many different MIVs and WEVs. The large number of vectors, combined with the biological—as opposed to physiochemical—processing of waste shifts the focus of the monitoring. Unlike the exogenous control system, in which monitoring determines the exact composition of the vectors, monitoring the endogenous control system measures the func-

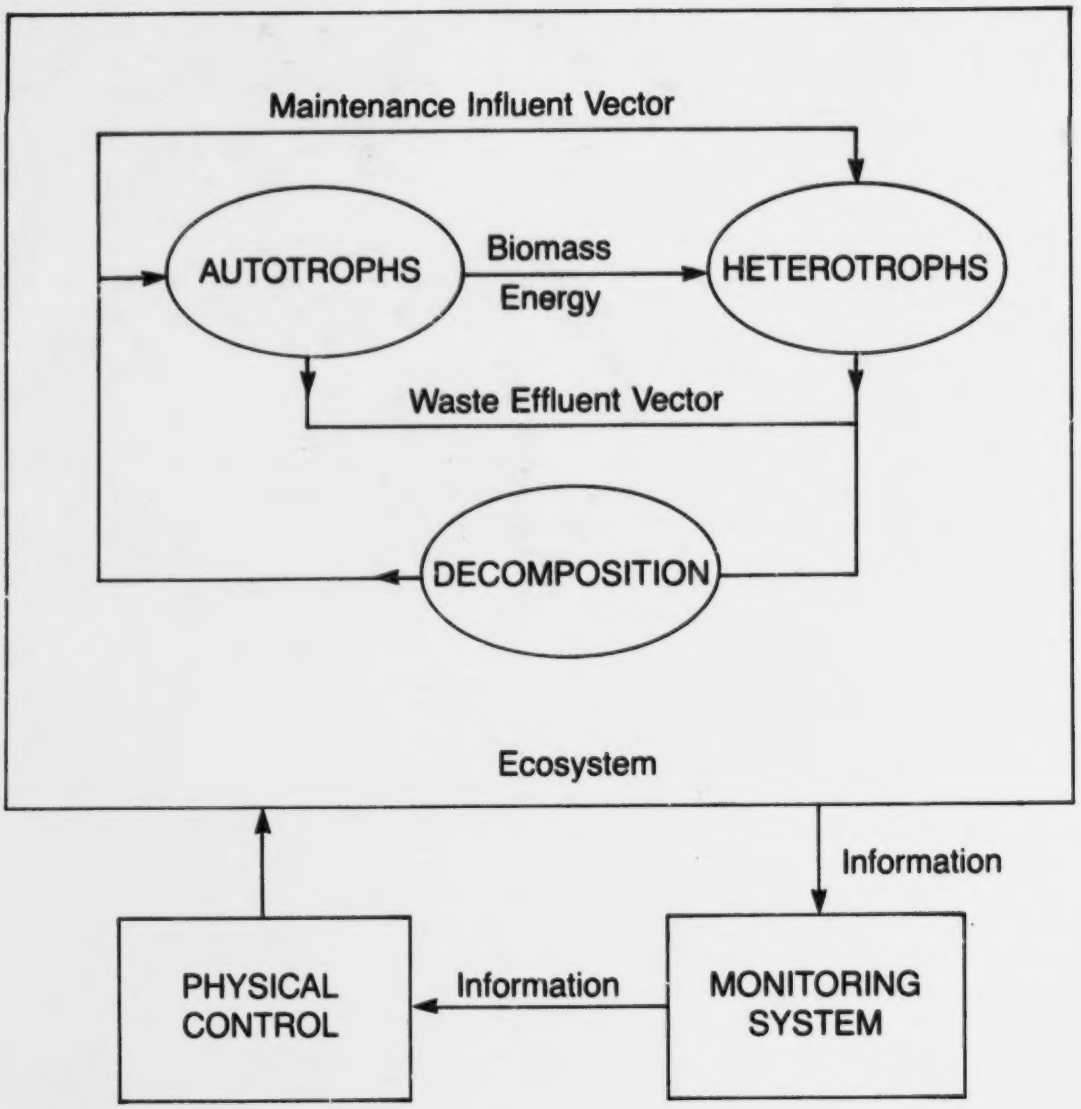

Figure 3. Endogenous control.

tioning of the biological system as reflected by integrative outputs. This shift in focus is possible due to a simple fact: If the endogenous controls are functioning well, the system as a whole should be functioning well. Any malfunction of the endogenous control mechanisms should be reflected by an imbalance in system function. The monitoring systems would record this imbalance, and humans could then attempt to return the system to proper functioning through limited manipulation. Consequently, integrative tests of the system's functioning, such as measuring the turnover time for nitrogen or the rate of energy transfer, become important monitoring devices and significant areas for research.

Initially, the regeneration of the MIV from the WEV would be carried out completely by biological means. Included would be soil-core processors and many of the biological processes conventionally used in waste treatment (i.e., activated sludge). Designing and improving such biological processing would be an important aspect of research (see Section 4).

Since the exact makeup of the many WEVs will not be known and waste streams will not be broken up into fractions, the biological processes for waste treatment must be capable of handling a generalized waste stream. Similarly, the species used for biotic production must be able to make use of a general nutrient stream (which, under the biological waste treatment regime, would be nonsterile).

The types of conversions that can occur during biological waste processing will be determined by the species of microorganisms and the types of environments included in the system. For example, in an aerobic environment, large organic molecules will, as a rule, be broken down into inorganic compounds with their important biological elements in the highest oxidation states. This conversion should be reasonably easy for a CELSS in which the reducing environments other than the guts of animals are kept at relatively low levels and at appropriate locations in the system. (It should be noted that plant and bacterial tissues are also reducing environments—in fact, no life can exist without them.)

The limited exogenous controls over these biological reactions differ significantly from those used in the wet laboratory. They are designed to control the endogenous mechanisms for self-regulation of natural ecosystems rather than to govern various physiochemical processes. These exogenous manipulations would consist of changes in the physical factors affecting the organisms that, in turn, effect the conversions. Specific controls might include altering temperature or atmospheric regimes to enhance or impede the reactions produced by microbial species. Moreover, humans may be able to add or delete specific reactions by introducing or removing the populations of particular microbial species.

Experimental work on systems that emphasize endogenous control would begin with the isolation in partially closed microcosms of ecosystem subvolumes such as soil circles, plastic bags immersed in lakes, and extractions of mixed organisms. Small systems of this type can be expected to deteriorate and experimental work would focus on extending their longevity and identifying the important functions that indicate their health. As before, these systems can be made more complex by introducing species or by increasing the degree of closure.

From this research, we would hope to gain insight into the failure characteristics of natural ecosystems and to understand better their endogenous controls. Such knowledge would enable us to monitor the biological component of a CELSS more effectively and to improve the design of the exogenous controls we impose on the natural ecosystem.

Program Synthesis

The systems embodying the two control strategies should prove complementary. It is essential that there be a rich exchange of information between researchers involved in the two main approaches and in the many component experimental programs so that, as experiments proceed, engineering controls and systems from the exogenously controlled system could replace their more troublesome or less efficient counterparts in the endogenously controlled system, and vice versa (e.g., the addition of an incineration step to the endogenously controlled system following a biotic decomposition process). Eventually the two approaches would yield a very limited set of processes and controls for regenerative systems that incorporate the most reliable and efficient features of both. This synthesis could serve as the basis for an operational CELSS.

This part of the RLSR program is summarized in the following lists. The rules of convergence are listed first; they are designed to guide research toward increasing complexity within individual experiments of the experimental programs.

1. Within an experiment, cheating vectors in the wet laboratory cannot be allowed to increase in magnitude.
2. Within an experiment, the degree of endogenous control in the biological approach should not be allowed to increase.
3. Information and technology should flow freely between workers involved with the two designs.
4. Special events and failures should be purposefully planned. The consequences of plants and animals dying, excess production, and contamination, as well as the subsequent reestablishment of components should be tested experimentally.

The objectives of an RLSR experimental program are summarized as follows:

1. To determine the necessary monitoring points.
2. To determine the composition of the WEV and MIV.
3. To reduce the cheating vectors to processing vectors.
4. To improve the efficiency of the engineering approach of complete combustion and resynthesis and of the biological approach of microbially mediated decomposition.
5. To determine the necessary degree of redundancy and replication.
6. To determine the magnitude (size) of buffer reservoirs.
7. To establish criteria of bound systems.
8. To combine information from the engineering and biological design approaches.
9. To test the system through repeated cycles of production and decomposition.

3. BIOTIC PRODUCTION

Overview

The plants used in a CELSS, as well as their experimental precursors, should be free of pests and diseases. It should be relatively easy to exclude nematodal, molluscan, crustacean, and other metazoan pests; it should also be possible to avoid bacterial and fungal diseases. Viruses pose a more difficult problem because some of them may be transmitted through plant seeds; it appears, however, that the elimination of recognizable pathogenic viruses should be possible. In addition to ridding the plants of all pests and disease, it may also be desirable to render them microbiologically sterile. This degree of sterilization would be used for gnotobiotic plant production and could be accomplished by extending the methods for removing pests and disease to all microbial species.

One major area of research in an RLSR program would be an examination of the desirability—indeed, the feasibility—of growing crop species gnotobiotically, as opposed to growing them with their associated microorganisms. The control mechanisms and the magnitude of the biological component associated with these two methods of plant production parallel the RLSR experimental program's bifurcation into exogenously controlled and endogenously controlled systems. Gnotobiotic plant production requires exogenously controlled systems, whereas raising crops with their normal array of microorganisms allows the use of naturally occurring controls. In this section, the ways in which these two methods mirror the strategies and systems associated with exogenous and endogenous control are discussed, and the key problems associated with biotic production are described.

Gnotobiotic plant production (usually by hydroponics) eliminates the microorganisms normally associated with the plant in nature. (See Coates, 1968; Heneghan, 1973; and Hale, 1969 for an introduction to various aspects of gnotobiotic research.) This reduction of the biological component of the system requires a concommitant increase in the care taken with the synthesis and the monitoring of the nutrient stream administered to the plant. The gnotobiotic method complements the use of a wet laboratory because the MIV created in a wet laboratory can be made sterile, its contents can be known precisely, and it can be manipulated to produce a desired nutrient solution. The requirements for gnotobiotic plant production, which minimize the biological component and maximize human manipulations and the need for a well-defined WEV and MIV, make this method for crop production compatible with the engineered system.

Conventional methods of crop production involve the normal assemblage of microorganisms, maximizing the system's biological component and reducing the need for exogenous controls. This approach complements the various biological methods for converting the WEV into a MIV because the microorganisms associated with plants in nature are integral parts of many elemental cycles. For example, both *Nitrosomonas* and *Nitrobacter*

are needed to convert ammonium ions into nitrates, which are the preferred form of nitrogen for some plants. Such soil microorganisms would play an important role in converting the WEV into a MIV, and these are only examples from a large microbial species set that may be extremely valuable. (See Dommergues and Krupa, 1978, for a collection of papers concerning some of these.)

Gnotobiotic Production in an Exogenously Controlled System

Although all other plant and animal species can be made microbiologically sterile before they are placed into a CELSS, microbial contamination will occur as soon as humans are introduced. Because complete human sterilization is extremely difficult—possible only when a child is born by Caesarean section and subsequently raised in a sterile environment—a 100 percent sterile environment for large-scale gnotobiotic plant production will not be possible within a CELSS if humans have direct contact with the plants. Separation of plants and humans by microorganism proof barriers would be extremely difficult to maintain over long periods, especially if manipulation of the plants is required. These obstacles may well preclude gnotobiotic production.

Many species of microorganisms are present in most soils. Plants normally have substantial populations of soil bacteria and fungi growing in association with their root systems in the rhizosphere. Large and healthy populations of microorganisms in the rhizosphere play an important role in protecting plants from invasion by pathogens. (See Baker and Cook , 1974 for a review; and Marx and Krupa, 1978; Hayman, 1978 on specific protection of root systems by mycorrhizal fungi.) Many microorganisms of the rhizosphere require for nourishment the organic material secreted by plant roots or root parts that die in the normal course of growth. Some microbes enhance nutrient uptake and growth of plants in return for secreted organics. Fungi contribute to plant nutrient uptake in soil and, at the same time, protect plants from pathogens (Hayman, 1978; Marx and Krupa, 1978; Harley, 1972). Certain rhizospheric bacteria also enhance plant growth through such postulated mechanisms as production of plant growth hormones or inhibition of competing rhizospheric microbes (Walker, 1975; Kloepper et al., 1980). Since the gnotobiotic method for growing plants excludes microorganisms from the rhizosphere, root secretions and dead root parts accumulate. This buildup may permit some of the microorganisms unavoidably brought into the CELSS by humans to expand their normally realized niches to the point that some of them could have deleterious effects on some of the plants. The probability of this happening is high enough to warrant research into the feasibility of gnotobiotic plant production in the presence of human-borne microbial species. Experiments in this area would assess the possibility of niche expansion and attempt to determine ways of preventing it.

Suggested Experiments for Biotic Production

Plants could be grown both gnotobiotically and with various degrees of their natural flora, and researchers would monitor the parameters important to a CELSS (e.g., productivity per unit area and volume). Replicates of the plants from each of the groups could be contaminated with microorganisms taken from human skin, feces, mouth, and naso-pharyngial washings. The parameters would be checked again for changes that might indicate any enhancement of or interference with plant processes. Research would

focus on isolating those species of human microorganisms thought to be responsible for any differences that did arise. Examination of the effects of various plant substrates on these interactions also should be included.

In the second phase of experimentation, the same procedure would be repeated, but the types of MIVs used to support plant growth would vary. Each must be tested because plant susceptibility to invasion by human microorganisms might correlate with diet. This phase of experimentation would be most important to the engineering approach, in which different MIVs can be supplied by changing the physiochemical processes of the wet laboratory.

Success in isolating the microbial species able to expand their niches would lay the foundation for additional research, and isolating the inhabitants of the human intestine—before they entered the CELSS—would be the next logical step. We feel that NASA should begin work in this area, particularly because of its importance in the selection of humans for the pre-enclosure experiments. Pre-enclosure quarantine of the humans will have an effect on their biota. The patterns of these responses should be investigated and their implications considered within the context of plant production.

Finally, it may be possible to detect major shifts in the microbial community that forecast trouble. Because classical techniques of plating and identifying microbes are so time consuming (Balish et al., 1977; Moore and Holdeman, 1974), new methods for determining the presence of microbial species should be investigated. (White et al., 1980, contains one such method which may be useful.) In addition, application (and perhaps further development) of combined fluorescent-antibody, autoradiographic, and energy-charge techniques should permit considerably faster, more accurate species identification and improved evaluation of the size and activity of populations of bacteria in a CELSS system (Fliermans and Schmidt, 1975).

Also, examination of bare-root hydroponics, sand culture, and use of various soil types needs to be combined with the above microbiological study, as well as with some of the waste-treatment problems discussed below (including the possible Si problem). As one moves from hydroponics through sand culture to soils, the available sites for microbial growth will increase in area and variety; this change will have a great effect on the microbe and root interaction. The interplay between different degrees of complexity in the microbiological and substrate community should be an interesting and productive area for research. Furthermore, it could provide a bridge for the hybridization of the two experimental strategies.

Along the same hydroponic soil continuum, the usefulness of plant substrate as a possible component in the total waste-treatment process will change considerably (the soil could be of considerable assistance, primarily through the activities of its microbiota). The amount of control required on the nutrient stream composition (for the plants) will change. In bare-root hydroponics, the composition of the nutrient solution will have to be very carefully monitored and controlled (Berry and Ulrich, 1968). This level of exogenous control may not be necessary, by contrast, for conventional soil systems because of the potentially enormous buffering effects of soil.

Finally, it is essential to identify the required and the detrimental plant and gas interactions, particularly the response of plants to atmospheric gases that include signal molecules. Ethylene is known to have complex effects on reproduction and development in some species (e.g., germination and ripening of fruit [Wheeler and Salisbury, 1980; Abeles, 1973 for an extensive review]). Other volatile organics are known to be selectively detrimental to different species. The entire matter of atmospheric quality and organism response must be understood and used as part of the control scheme.

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4. WASTE TREATMENT AND DECOMPOSITION

Overview

A distinguishing feature of a CELSS is that it is a materially closed biological system. To achieve this closure, a CELSS must include waste-treatment processes that convert completely the elements of the WEV into forms that allow their reintroduction into the biological cycle through the MIV.

The number of forms of the important biological elements (e.g., C, N, P, O, H) that can be incorporated into the simplified biological cycle, which is characteristic of a CELSS, is small and quite limited in comparison with the total number of possible compounds that could be created by the different processes for waste treatment. For example, most plants can use nitrate (NO_3-) or ammonium ions (NH_4+) as a source of nitrogen, but they are unable to use nitrite (NO_2-) or atmospheric nitrogen (N_2). Such specificity may prove a problem in designing the waste-treatment processes, since one process that is effective at converting carbon compounds to carbon dioxide, which is a form easily used by plants, might also convert nitrogen compounds to nitrite or atmospheric nitrogen, which are unusable by plants. Nitrite and atmospheric nitrogen can be made into forms usable by plants with secondary treatments, either chemically or biologically (e.g., biologically, by the bacteria *Nitrobacter* and *Rhizobium*).

Processes for waste treatment differ in the efficiency with which they convert the important biological elements of the WEV into forms readily useful to the biotic component of a CELSS. As a result, a suite of processes will have to be designed in which each process is tailored to specific elements. To do this, the precise makeup of the different effluents in relation to a given input must be known. Therefore, the initial research for waste treatment in a CELSS experimental program should focus on identifying the inputs to and outputs from specific waste-treatment processes.

Experimental work should be undertaken on the inputs and outputs of each of these processes. In all experiments, thorough analytical work should be done on the forms, oxidation states, and availability of the important elements and micronutrients. Special attention should be paid to the distribution of these elements among the three effluent vectors (solid, liquid, and gas). Such analyses will provide the knowledge needed to devise auxiliary processes that will ensure optimal cycling between each element. The relation between the inputs and outputs, as well as the control characteristics of environmental conditions, need to be developed.

The efficacy of decomposition must be evaluated relative to the desired result—regenerating food safely and reliably. Although a chemical analysis of the inputs and the outputs will provide the data for designing a system, experimental validation is necessary. The final test of the efficacy of a decomposition process must be experiments in which

crops are grown from the effluents. These experiments should always be carried through several harvests (i.e., circulating nutrients through several cycles of the loop) to discover any possible areas of backup or accumulation.

Inputs vs. Outputs

The processes chosen for waste treatment will not affect the composition of the WEV directly. In fact, the reverse will be true: The makeup of the WEV will influence the types of processes chosen. Some processes may not be able to act effectively on certain WEV compounds, and, in extreme cases, particular compounds may interfere with the functioning of a process. Additionally, different compounds of an element may not always be converted to the same form in the effluent; in some cases their ultimate forms may depend on the form of the input. Specific examples of these problems are dicussed in the last two subsections of this section, in which the individual processes for waste treatment are described.

The components of the WEV that consist of wastes from plant production may determine whether biological or physiochemical methods are chosen for waste treatment. As discussed in the section on biotic production, microbial contamination from humans may preclude gnotobiotic production because of the possibility that these microorganisms might expand their realized niches to become plant pathogens. The microorganisms used in the biological processes for waste treatment might pose a similar threat. To test the compatibility of gnotobiotic production and biological waste treatment, the experiments described in the section on biotic production should be repeated and should include the microorganisms of the waste-treatment process in addition to those of humans .

Another potential problem that could affect the choice between biological and physiochemical processes for waste treatment is the presence in the WEV of silicon from plants grown in soil or similar substrate. When subjected to some of the processes for physiochemical waste treatment (such as heat), silicon generally forms insoluble silicates with nitrogen and phosphorus. Such compounds could lock up important quantities of these and other important biological elements, thereby interfering with the functioning of the biological cycle. Experiments should be conducted to determine the extent of this problem and to discover processes that dissolve these compounds and free the important biological elements. The formation of insoluble compounds may prevent direct physiochemical processing of wastes from the plant production module. Alternatively, experiments should be conducted that would determine whether significant reductions of silicon in the input stream would solve this difficulty in the output stream. Silicon cannot be eliminated completely because it is a nutritional requirement of some important food plants (Bennett and Parry, 1980) and of humans (Guthrie, 1979).

Outputs

A detailed knowledge of the composition of the effluent from each process for waste-treatment, starting with a known set of inputs, is necessary for selecting and assembling the combinations of processes to be included in a CELSS. For research purposes, the effluent can be classified into four general categories that are not mutually exclusive: inorganic compounds, salts, trace metals, and gaseous effluents. This section discusses the general importance of the four in relation to overall CELSS function. Subsequent

subsections examine the specific problems of these categories in relation to individual waste-treatment processes.

Inorganic compounds. Because the CELSS biological cycle reincorporates the bulk of the important biological elements as inorganic compounds, research should focus on waste treatment methods that would maximize the number of available inorganic compounds exiting the system. The initial research effort would catalog various waste-treatment processes and identify the forms of the inorganic compounds and any partially oxidized organic compounds produced. The data comparing output and input from each process could be combined to help determine specific combinations of processes that would produce the important biological elements in their highest oxidation state.

Although it would be easier to examine the functional characteristics of a waste-treatment process, this approach is insufficient for designing the CELSS waste-treatment system. For example, the degree of carbonaceous oxygen demand (COD) removed is not equal to the quantity of CO_2 produced; although the partial oxidation of an organic compound to a carboxylic acid decreases COD content, it does not produce CO_2. This illustrates the need in the RLSR program to identify the precise output of a waste-treatment process.

Salts. Separation of salts into highly disaggregated solutions is extremely difficult and may be impossible in the waste-treatment processes considered in this report. This difficulty may present serious obstacles to the use of hydroponic plant production methods that require nutrient solutions with very specific salt contents (Berry and Ulrich, 1968; Berry, 1978). Although a high degree of separation may not be feasible, some degree of separation can be achieved through either precipitation and redissolution or ion-exchange. General research within the area of precipitation and redissolution should attempt to identify acids and bases for use on specific salts in each method. Although waste treatment may neither need nor be able to achieve a high degree of salt separation (one research goal may be to minimize the degree of separation necessary), research should be undertaken to devise methods for removing NaCl from the liquid effluent. This separation may be important for any CELSS that depends on plant production and could be particularly crucial to soil plant systems in which inadequate irrigation procedures could lead to a buildup of NaCl in the soils used for plant production. Alternatively, separation at the input stream (e.g., separate processing of urine) should be investigated and compared with separation later in the processing stage. Storage of unpurified salts and their replacement from stores may be initially less costly than separation, but as the cheating vectors are reduced, use of stores (nutrient and waste) must be reduced as well.

Trace metals. The problem of metals being made biologically unavailable for reincorporation to the biological cycle by waste treatment should be minor, although there was uncertainty on this point among members of the study group. Most of the processes for waste treatment will not be severe enough to form insoluble oxides from the dissolved metallic elements present in the WEV. (Although some microbial species can remove certain heavy metals selectively, the separation of these metals would be just as difficult and complicated as the separation of salts, and it would present the same obstacles to hydroponic production.) Nevertheless, some of the waste-treatment processes may be severe enough to corrode metal equipment and introduce heavy metals into the liquid effluent. Because it is possible for these metals to accumulate in certain storage pools of the CELSS biological cycle, tests should be devised to monitor the quantity of metals in

the effluent. Also, any experiments designed to test the feasibility of physiochemical processes for waste treatment should be carried through several generations of production and decay, and the various system compartments should be monitored for metals accumulation, as well as other deleterious effects.

Gaseous effluents. All processes for waste treatment examined in this report will release into the atmosphere some compounds that are potentially toxic or unavailable to the biological cycle. Since the concentration of such compounds in these emissions will be extremely low, gaseous effluent from all the processes should be monitored with particular care. Gaseous effluents from plants, humans (e.g., flatulence), and other animals that might be used will also have to be monitored because atmospheric treatment may be required to remove some of them.

These atmospheric emissions can generally be classified as particulates and mists, reduced gases (e.g., CO, NOx, SOx, hydrocarbons), and hydrogen halides (e.g., HCl, HF). There exists for each of these groups a contaminant-specific pollution control technology, and initial research in the area of gas scrubbing should investigate the effectiveness of each technology. For example, particulates and mists are removable by inertial devices, fabric filters, or electrostatic precipitators, whereas reduced gases are removable by catalytic oxidation, ozone, or scrubbing with oxidant solutions (e.g., H_2O_2, permanganate). The composition of the contaminants in the gaseous effluent and effective methods for secondary treatment are discussed later in relation to the individual processes for waste treatment.

Modeling

No single waste-treatment process can optimize the availability of inorganic compounds containing the important biological elements; therefore, suites of processes will have to be designed for certain elements in order to enhance recovery. Waste treatment will have to handle at least three sets of wastes (urine, feces, and excess plant production) through perhaps four different waste-treatment processes (wet oxidation, incineration, composting, and activated sludge), and produce an effluent for three different end uses (drinking water, nutrient solutions, and breathable atmosphere). Based on these requirements, the waste-treatment system could have as many as 36 (3 x 4 x 3) basic configurations. Computer simulations of the more likely basic configurations, based on input and output data gathered for each of the processes, will be valuable tools for screening various combinations before this area of research moves to an advanced experimental stage.

It is unlikely that any one of the 36 possible configurations for waste treatment would yield all the inorganic compounds of the important biological elements in forms available for biological uptake. Thus, there could be a continual loss of some elements from the biological cycle. Modeling would enable researchers to compare the effects of losses occurring through the various combinations, to calculate the quantity of each of the biological elements that must be included in CELSS, and to examine the need for buffer reservoirs.

The quantity of a particular element that must be included in a CELSS depends on the size of the biological buffer pool, the importance of the element to the cycle, and the time the element remains in each of the storage pools. For example, the minimum quantity of carbon needed would depend on the number of persons in the CELSS and on carbon's

relative stochiometry within the cycle. Additional carbon also may be needed to compensate for that element's different residence times in various storage pools. Carbon might spend only a short time in the atmosphere, a longer time in the waste-treatment system, and a still longer time in plants. Should this accumulation occur, a buffer reservoir would be needed to ensure that the carbon buildup in the plants did not disrupt the biological cycle by depleting the carbon in the atmospheric pool. Modeling would simulate these residence times and help calculate the size of a buffer system that would release carbon into the biological cycle in order to keep it functioning. Modeling would also help in selecting the combinations of manipulation and natural processes (including plant growth) that would minimize the size of the buffer pools required.

Scientists from a variety of disciplines will use the results of any modeling carried out in the RLSR program. To make the models and their results understandable, a standardized format should be established. This format would include flow diagrams that explicitly show state variables, flows, and points for monitoring and controlling the system. Such a format also would make the results of this RLSR program accessible to scientists from other fields.

Treatment Processes—Physiochemical

Overview

Two physiochemical processes for waste treatment, combustion and wet oxidation, are examined in this section. Both methods use heat and pressure to break and re-form chemical bonds in accordance with the physical properties of the compounds of the WEV.

Physiochemical waste-treatment processes are generally easier to control than their biological counterparts. Rather than depending on a healthy biological flora, physiochemical processes work in conjunction with the physical properties of a compound. This gives them a reliability and ease of control that makes them compatible with the exogenously controlled system described earlier ("Inputs vs. Outputs").

Combustion

Combustion is the rapid exothermic oxidation of combustible elements within a fuel stock. Methods used for combustion range from incineration, which is complete combustion in the presence of excess oxygen, to pyrolysis, which is destructive distillation, reduction, or thermal cracking and condensation of organic matter under heat or pressure or both in the absence of oxygen. Partial pyrolysis, or starved-air combustion (SAC), is incomplete combustion; it occurs when not enough oxygen is present to satisfy incineration requirements. Biological elements in their highest oxidation state are, as a rule, easiest to reincorporate into the biological cycle. Therefore, only incineration and SAC were selected for consideration in this report based on their potential practicality for waste treatment in CELSS.

In general, the combustion of wastewater solids entails both drying and burning. These two steps can take place simultaneously or they can be separated both spatially and temporally. Regardless of the technology used, the sludge is dewatered, dried, and—

once it is in a semisolid state—heated until it burns and its combustible elements are oxidized.

The energy for these two heat processes can either be obtained solely from the sludge (an autogenous process), or can be augmented from outside sources. The quantity of combustibles per unit mass of sludge determines whether a combustion process will be autogenous, and a value of 2.33×10^4 kJ/kg combustibles is frequently used for calculating the heat value if the sludge is burned (Noyes, 1980). The quantity of energy that can be provided by sludge for running the combustion process depends on the amount of combustible solids in the sludge; generally, the minimum required for autogenous combustion, which may be preferable in a CELSS, is 30-35 percent (Noyes, 1980).

Sludge with a solids content of this level is difficult to obtain with conventional dewatering techniques; therefore, supplemental fuel may be required for the combustion process. This supplemental energy could be supplied by mixing other material with the sewage sludge to create a furnace feed with a heat value greater than that of the sludge alone. Plant wastes and excess plant production have a large heat value and may provide an appropriate supplement. Combining this unusable plant production with sludge would satisfy the requirement for recycling plant waste while making autogenous combustion possible within a CELSS.

Both incineration and SAC should be investigated as possible processes for waste treatment. (See Noyes, 1980, for additional discussion of the various combustion technologies.) In both processes, wastewater solids are mechanically dewatered before being sent to the combustion furnace to be dried further and burned. If strict limits are set on the quantity of organics in the off-gas, the waste can be sent to a catalytic oxidation unit. However, because of the low heat content of the resultant off-gases, the afterburner would require additional energy inputs. Furthermore, in order to ensure that the oxidation is complete in incineration, oxygen must be supplied in quantities exceeding the theoretical level set by stoichiometric relations. This excess is needed because of incomplete mixing between the dried sludge and the atmosphere.

The major advantage of incineration over SAC is that it oxidizes most of the important biological elements to their highest oxidation states; therefore, most of these elements are in forms that can easily be reincorporated into the biological cycle as nutrients for plant growth. In addition, this method of waste treatment could provide an easily managed point of control for the levels of O_2 and CO_2 in the system.

Starved-air combustion is the alternative combustion process for waste treatment in a CELSS. Again, wastewater solids are mechanically dewatered before being sent to the combustion furnace. Under SAC conditions, the quantity of oxygen present is reduced between 30 and 90 percent of the stoichiometric level required for complete oxidation of the sludge (Noyes, 1980). The remaining material, which is partially oxidized, exits through the furnace as gaseous effluent with a heat content of 3.35×10^4 kJ/m^3 and can be fully oxidized in a catalytic oxidation unit. Catalytic oxidation uses relatively small amounts of oxygen. Starved-air combustion accomplishes the oxidation sequence for sludge with less oxygen than does incineration.

In addition to its reduced oxygen requirements, the SAC method has several other advantages. Operation of a multiple hearth furnace (MHF), discussed by Noyes, 1980, under SAC conditions allows loading rates 30-50 percent higher than optimal incineration rates. Even though the timing and the amount of waste oxidized at each burn can be carefully controlled within the incineration process, the SAC process is more stable and easier to direct because it can be controlled by adjusting the rate of gas input. Starved-air

combustion also produces fewer toxic emissions and larger particulates (which are easier to remove) than incineration.

Research issues. The predominant form of inorganic compound that the important biological elements take as they leave the combustion process depends on the combustion method. In general, the gaseous effluent from the incineration process contains inorganic compounds in their highest oxidation states, but off-gases from the SAC process are only partially oxidized. Although this gap can be reduced in the afterburner, important differences still remain.

For example, the two combustion methods create different compounds of nitrogen. Incineration yields nitrate (NO_3-) and nitrite (NO_2-). Although the former is readily usable by plants, the latter is phyto-toxic . Yet, in aerobic environments—even at the relatively low concentrations likely in the atmosphere of a CELSS both of these nitrogen compounds could pose serious health threats to human beings. Effective sinks, including soils, water, and their attendant plants and microorganisms, may be relatively easy to employ in eliminating this problem. By contrast, the SAC process converts nitrogen to ammonia, which leaves the furnace in the off-gas and is converted to atmospheric nitrogen (N_2) and water in the afterburner. This form of nitrogen is safe for a CELSS atmosphere but it is unavailable to most plants. Converting ammonia to atmospheric nitrogen would have a serious effect on the nitrogen cycle and might complicate the job of closing it. *Rhizobium* or other nitrogen-fixing species or processes may be required to offset this loss (although the compensation process would result in higher energy demand).

The forms of the inorganic compounds and their availability for reincorporation into the CELSS biological cycle are major targets of research into the combustion process. For example, despite the fact that the ashes constitute the bulk of the solid effluent from incineration, very little is known about their molecular composition. In addition to the ashes, some condensates (e.g., tars and oils) formed by SAC may be highly carcinogenic. The molecular composition and the availability of inorganic and organic compounds contained in such substances should be determined.

The severe environments that occur in physiochemical waste-treatment processes could encourage the formation of insoluble silicon precipitates (by definition more troublesome under incineration than SAC). Research should examine the effluent from both processes for any insoluble compounds and determine the magnitude of this problem.

Several advantages associated with the use of combustion as a waste-treatment process make it attractive for use in a CELSS. Since it is quick, wastes would have a short residence time in the treatment system. As a result, elements would not accumulate in the waste system, and the absolute size of the various element pools could be reduced. Additionally, combustion destroys organic toxins and pathogens completely, making possible the direct application of effluents to gnotobiotic plants without fear of microbial contamination.

Combustion also has several disadvantages. Large quantites of energy are required for drying and burning waste, and, although the participants of these workshops assumed an unlimited energy supply, a method must be found for eliminating the excess heat produced by the combustion process.

The effluents from combustion may also cause problems. Pollutants in the exhaust gases must be removed by methods described earlier in this section ("Gaseous Effluents"). Certain fractions of the ash may be especially insoluble and may not react with either acids or bases. In addition, the molecular composition of the effluents is extremely sen

sitive to combustion conditions (e.g., waste particle size, moisture content, composition of the combustion air supply, and solid and gas residence times) and therefore could vary greatly. This sensitivity might present a severe problem for controlling a waste-treatment system that is designed to optimize the availability of biologically important elements for reincorporation into the biological cycle, and the nature of this sensitivity constitutes the major area of research in combustion processes.

Research priorities. The most important area for research is an examination of the effects of various combustion conditions (e.g., turbulence, time, and temperature) on the composition of gaseous and solid effluents. The amounts or forms of nitrogen, sulfur, and CO produced may be influenced by the length of the period during which combustion takes place, the temperature at which it occurs, and the extent of mixing. The effects of other conditions (e.g., proportion of solids in feed solution, quantity of excess oxygen) on the composition of gaseous and solid effluents should also be investigated.

The composition of the ash produced should be examined carefully. The forms of carbon, silicon, nitrogen, and boron in the ash should be determined precisely, because they are the most likely group of elements that may be fused into insoluble compounds. Hydrochloric acid and H_2SO_4, which can be recovered from the gaseous effluent by scrubbing, could be used to break down such compounds. These acid mediated reactions may be slow enough to become the rate-limiting step in CELSS waste treatment. Research should focus on methods for accelerating the reaction time.

Wet Oxidation

Wet oxidation is a relatively new method of waste treatment; it uses high temperatures and pressures to decompose large organic molecules. (See Wilhelmi and Knopp, 1979, and Meissner and Modell, 1978, for more information about wet oxidation.) To make waste amenable to wet oxidation process, it must be converted to a slurry that is 1-10 percent solids by weight and pressurized to 41-174 kg/cm^2 [600-2,500 psia]. This slurry is combined with an atmosphere, which may range from a normal mixture of atmospheric gases to pure oxygen, and is heated from 150°C to 300°C. The mixture is agitated vigorously for 15-60 minutes.

The mixture undergoes two well-defined phases of oxidation kinetics. A large percentage of the total reduction of COD occurs in the first phase, which lasts about 20 minutes. During the second phase, more recalcitrant organics and partially oxidized intermediates produced in the first phase are oxidized further. (Although the more recalitrant organic compounds take longer to oxidize, most of them are biodegradeable.) The products of the slurry atmosphere mixture are then cooled and separated into gaseous, liquid, and solid residues.

The forms of the important biological elements (e.g., C, N, H, O, P) produced by wet oxidation depend on the severity of the temperature and pressure regimes within the process. Mild wet oxidation and Zimpro wet oxidation are the two processes used in commercial applications. In the mild wet oxidation process, temperatures between 150°C and 250°C and pressures of 41 kg/cm^2 [600 psia] are used; in the Zimpro process, temperatures range from 200°C to 300°C and pressures from 41-105 kg/cm^2 [1,500 to 2,500 psia]. The degree of oxidation can be pushed beyond that achieved with commercial methods by increasing the temperature and pressures of the oxidation process. At very high temperatures and pressures, the solubility of oxygen in water increases sharply,

which may make a single-phase reactor practical. This single-phase reactor would simplify the process and increase the degree of oxidation.

Research Issues. As with many of the other waste-treatment methods, a detailed knowledge of the inputs to and outputs from the wet oxidation process is lacking. Our knowledge is more comprehensive regarding the degree of COD removal. The mild wet oxidation process removes 60-70 percent COD, the Zimpro method removes 70-95 percent.

However, as mentioned earlier, the percentage of COD removed by a particular process is not equivalent to the amount of CO_2 it produces because the partial reduction of carbon decreases COD but does not necessarily yield CO_2. Research is needed to determine the quantity of CO_2 produced relative to the level of COD reduction under a variety of temperature and pressure regimes.

Another area of research related to the degree of COD removal is the identification of intermediate forms of carbon resulting from incomplete oxidation. Some of these products, such as carboxylic acids of low molecular weight, are particularly resistant to further oxidation; they cannot be oxidized completely without first undergoing other kinds of treatment. The forms and relative quantities of the intermediate carbon compounds are important considerations in the selection of the secondary processes used to treat them.

The forms of the important inorganic compounds produced by wet-oxidation processes have great significance as far as the biological cycle is concerned. For example, inorganic compounds of nitrogen and phosphorus are necessary for plant growth, but plants can use them only in a limited number of inorganic forms. Despite the importance of such information, very little is known about the inorganic compounds produced by the various processes of wet oxidation. They need to be identified so that the feasibility and desirability of different waste processes can be evaluated and the availability of inorganic plant nutrients can be monitored and controlled.

Some limited research has already been done in this area. Because mild wet oxidation has been used commercially for conditioning sludges, its output has been examined for possible use in soil enrichment. This research shows that the nitrogen is rendered soluble and available to plants, but that phosphorus is made somewhat less so.

The other commercial process for wet oxidation, the Zimpro method, has been used for waste treatment rather than sludge conditioning; therefore, little is known about the inorganic forms of nitrogen, phosphorus, and other important biological elements it produces. Serious doubts exist about the availability of the inorganic compounds that result from Zimpro and the other wet-oxidation methods with extreme temperature and pressure regimes. So far, the biological availability of inorganic compounds in the residue has not been determined.

As discussed previously, the form of the inorganic compounds may also be affected by the method used for plant production. If common soil types are used, the plant matter fed into the wet oxidation system may contain appreciable quantities of silicon, which can lead to the formation of silicates that are difficult or impossible to solubilize. If incineration was substituted as a waste-treatment method, the problem could be worse. Conversely, silicon levels in hydroponic plant solutions can be controlled more readily, and waste from plants grown using this method are less likely to be precursors to insoluble silicates formed during treatment processes. Research should be conducted on the solubility of organic and inorganic compounds generated by the different methods of plant production.

The gaseous effluents from the more severe wet-oxidation processes will contain some organics (CHx, low-molecular-weight organic acids), nitrogen compounds (NO_2, N_2O, NO, NH_3), small quantities of CO, and trace levels of sulfur oxides, all of which must be determined. The off-gas therefore, will have to be treated in an auxiliary process (e.g., catalytic oxidation) to return inorganic compounds in their proper oxidation states for reincorporation into the biological cycle. In addition, the effect of such auxiliary processes on system stability will need to be considered.

Since the conditions of wet oxidation are not severe enough to lock dissolved metallic elements into insoluble oxides, these elements will remain in the liquid effluent. Conditions could, however, be harsh enough to corrode the equipment and to introduce metals into the liquid effluent. These hazardous metals might accumulate in the food chain, entering via the liquid effluent as part of the MIV. This possibility needs to be considered, since such metals might not become apparent until the nutrient solutions have cycled through the closed loop several times. Therefore, experiments for each waste process should be conducted for many generations, during which plants would be grown and degraded through a closed nutrient loop.

Despite the unknowns of wet oxidation as applied to CELSS, it is one of the more advanced processes for rapid degradation of wastes. It has been shown capable of accommodating some toxic wastes, but its various costs are appreciable. Using the wet-oxidation effluent to regenerate nutrients for agriculture has received some attention in terrestrial applications, but the work has been confined to wastes treated under mild wet-oxidation regimes. Further, such studies have generally been done under poorly controlled conditions and with inadequate analytical methods. Any new developments stemming from RLSR may lead to improved terrestrial applications.

Treatment Processes—Biological

Overview

Biological decomposition of organic wastes in a CELSS could be accomplished through the use of either activated sludge systems, such as those employed in modern municipal sewage treatment plants, or composting. The basic distinction between the two processes is the quantity of water retained in or mixed with the wastes before decomposition begins. These distinctions cause fundamental differences in rates of processing, nature of end products, and potential use of the sludge produced.

Activated Sludge

A modified high-density, activated sludge system would correspond with an aqueous system (Haug, 1979). Such systems use oxygen, either pure or as it is available from air, to convert a wide range of organics to CO_2, H_2O, and cellular residues. Some organic molecules are resistant to biological breakdown and are degraded very slowly (Shuler, 1980). The catalysts for these reactions (generally operating at 15°C to 50°C) are bacteria, yeasts, protozoa, and some fungi—organisms normally present in the input streams. The ratio of various types of organisms to one another is in a dynamic balance and can be altered by changing flow rates, temperature, pH, etc.

yeasts, protozoa, and some fungi—organisms normally present in the input streams. The ratio of various types of organisms to one another is in a dynamic balance and can be altered by changing flow rates, temperature, pH, etc.

A typical aqueous activated-sludge unit consists of an aeration basin, a settling tank, and a recycle pump. The influent sewage stream to be treated is normally dilute (ranging from 300 ppm COD for domestic waste, up to 30,000 ppm COD for certain industrial wastes). Typically, the ratio of the liquid volume in the aeration basin to influent flow rate results in a liquid residence time of 2 to 10 hr. If conditions are chosen correctly, the biological cells flocculate to form relatively large and dense colonies. The effluent from the aeration basin is sent to a gravity settling basin or clarifier. A clarified effluent, nearly free of suspended material and cells, exists at the top, and a concentrated sludge occupies the bottom. This sludge, which may be 0.5 to 10 percent solids, contains cells (about 15 percent of which are alive) and residues of incompletely consumed particulates. Most of these solids are returned (or recycled) to the aeration basin. This recycle maintains a high concentration of cells in the aeration basin and ensures the rapid capture of soluble and colloidal material. Additionally, cell recycle ensures the biological catalysts sufficient opportunity to degrade the more difficult components in the feed stream. Cell recycle essentially increases the average residence time of a cell in the system.

Generally, aqueous systems are operated with mean cell residence times of 3 to 15 days. Residence times beyond this range normally do not result in cultures with good settling properties. Instabilities in the operation of activated sludge units can usually be traced to environmental conditions (e.g., flow and temperature), that cause a shift in the ratios of organismal types and thereby lead to the formation of small flocs with poor settling properties. As a result, the quantity of suspended solids in the clarified unit rapidly rises to unacceptable levels, and the quantity of cells available for recycle decreases, leading to less efficient uptake and metabolism of influent wastes.

Mean cell-residence time cannot be increased to infinity (i.e., total cell recycle) because the portion of material not susceptible to reasonably rapid biological breakdown in the tank would build to infinitely high levels. Consequently, a portion of the sludge from the clarifier is typically wasted (the quantity of entering solids wasted usually ranges from 20 to 25 percent). Under special conditions, the quantity of sludge wasted may be reduced to 5-10 percent of total solids (except dissolved salts) entering. It could be treated further by physiochemical or biological techniques (e.g., composting), or the sludge could be used as a sink, if food components are consumed routinely from storage.

The biological flocs are often very efficient at removing heavy metal ions; they may concentrate metal ions by factors of 2 to 1,000. Thus, the biological system might selectively remove many of the metals in the closed cycle. Such metal removal must be monitored so that make up metals can be added if necessary.

In most aqueous units, almost all of the nitrogen may exit in the form of NH_4+ (or organic N in the sludge that is wasted), sulfur will be in the form of SO_2, and phosphorus will exit largely as orthophosphates (soluble) in the clarified liquid (and organic S and P in the sludge). If pH levels rise too high (8.0), NH_3 will exit the reactor in significant quantities via the gas phase. If the mean cell residence time is greater than 10 days, the organisms *Nitrosomonas* and *Nitrobacter* can bring about substantial conversion of NH_4+ to NO_3- (Hesseltine, 1977).

These units often use a two-stage system. The first reactor is operated to ensure significant destruction of COD, and the second is used to encourage nitrification (i.e., NH_4+ to NO_3-). The operation of the second reactor is analogous to that previously

described. Two reactors are often used to ensure high mean cell-residence times and to prevent formation of a poorly settling sludge in the first reactor system as a result of the nitrification process. If the nitrified waste is not kept aerated, denitrification (NO_2- to N_2) will occur. Such a reaction would be undesirable in the context of CELSS.

Composting

In contrast to the aqueous biotic oxidation system, semisolid biotic oxidation follows terrestrial models of composting (Berry, 1978; Coates, 1968), solid substrate fermentations (Dommergues and Krupa, 1978; Danielson, 1973) or natural decomposition (Haug, 1979; Antonie, 1977; Abeles, 1973; Heneghan, 1973). The low water content encourages the growth of many fungi and discourages the growth of many bacteria. In addition, the lower water content would reduce the weight of the system. The fungi tend to grow more slowly but are generally more efficient at the biological oxidation of lignin or cellulosic materials. In the absence of a well-mixed aqueous phase, mass- and heat-transfer gradients are established, resulting in a heterogeneous reaction system. Often the physical process of mass and heat transfer will control reaction rates. The rate of decomposition in such systems can often be accelerated by reducing material volume, then placing it in a rotating drum reactor (Dommergues and Krupa, 1978; Danielson, 1973). The residue from such decomposition serves as an ideal terrestrial substrate for plant growth. In terms of CELSS, semisolid biotic decomposition might be most usefully employed on the portion of the waste high in lignin and cellulose residues (e.g., plant residues and the waste sludge from an aqueous biotic oxidation unit).

It should be recognized that the special conditions and constraints imposed by the operation of a CELSS unit may lead to composting designs that are significantly different from Earth-bound systems. This would be particularly true for aqueous biotic oxidation. Because wastes may be collected separately and stored, it will be possible to provide an influent stream of significantly more constant composition and flow rate than is typical of terrestrial units. A more constant input will improve the stability characteristics of the reactor.

Additionally, most terrestrial system waste streams arrive in very dilute form. In a CELSS, a much more concentrated waste can be generated, offering the possibility that the volumetric efficiency of such decomposition units can be greatly improved. The special environment within a CELSS allows for more precise control of temperature, dissolved oxygen, and pH. These parameters can be held more constant, thus increasing stability. They also allow operation at unusual conditions (e.g., 50 C).

Finally, gravity settlers may not make sense within the context of CELSS. Cell separation using ultrafiltration (Brown and Lester, 1979) may be an attractive alternative, since that process can remove more than 99 percent of COD from the liquid effluent. If gravity settling is not used, the system will not be restricted to operating conditions that produce flocs, and because unflocculated cultures are just as effective in decomposition, a wide range of operating conditions could be explored. Additionally, the stability of the reactor would be greatly improved, because the main cause of instability in terrestrial units is the failure of the gravity settler to capture and return suspended solids.

The advantages of biological waste treatment are as follows:

1. The liquid and gas effluents would be compatible with plant growth and would contain fewer chemical toxins than effluents from physiochemical treatment systems, which require a more extreme environment.
2. Biological systems generate CO_2 at fairly constant rates, whereas mechanical systems produce periodic pulses. The continuous output of the biological systems may be less stressful to small, relatively unbuffered CELSS.
3. Even if plant growth and harvest were reasonably continuous, the carbon stock in the production module will fluctuate. The biological waste management system could serve as a better place to buffer/store carbon stocks.
4. The formation of a partially oxidized feedstuff from waste can be better accomplished by a biological process than by a physiochemical process. If the residue could be used as animal or human food (Kargi et al., 1980 ; Dommergues and Krupa, 1978; Finger et al., 1976; Kammermeyer, 1966), then the complete construction and destruction cycle for organics could be short-circuited. This short-circuiting could result in a decreased requirement for plant growing space and consequently a reduction in weight.
5. In general, biological systems favor the production of nitrates over ammonia and cause less denitrification than mechanical systems.
6. Most terrestrial waste-treatment systems use the activated-sludge system; therefore, a potentially large knowledge base already exists from which to draw.
7. Biological systems can be repaired if breakdown occurs or if the active system becomes unbalanced by initiating a new compost or sludge with a new innoculum. Supplies of material sufficient to repair a large number of system failures could be carried on board space vehicles with very little increase in volume or space requirements.

Among the disadvantages of biological treatment is a relatively slow turnover time, potential for epidemic populations, slow start-up time, and difficulty in control. In addition, biological processes tend to produce more humic substances—recalcitrant organics that would need further treatment by, for example, incineration. A general comment applies: These biological systems for decomposition are centered on organisms that can be viewed as highly versatile, compact, self-repairing decomposition factories. It may be far more difficult, however, to obtain adequate knowledge of and control over these factories than would be the case with nonliving physiochemical waste treatment processes.

Research Issues

Aqueous biotic oxidation. Material balance information for terrestrial systems is incomplete. Moreover, since a bio-oxidation unit in the CELSS context would be operating in a spatially confined condition, the need for material balance is vital.

1. How do various processing techniques alter the composition of the input and output streams? Knowledge of the composition of each waste (by element for at least the 15 most common elements and some of the heavy metals, and by compound for residual organics, nitrogen, and phosphorus) is necessary to guarantee accurate monitoring and prediction of the buildup and loss of essential or toxic materials. All three exit streams, the liquid effluent, the solid residue, and the gas phase, must be monitored. It is anticipated that the gas phase, after a demisting step, will contain very little in the way of objectional or nitrogenous compounds, but this needs experimental verification, particularly with regard to N_2O.

2. The microbial flora will be developed from the flora present in effective biological waste-treatment units; environmental (or design) variables may modify this character of the flora, although exogenous organisms may be injected into the system for greater effectiveness and control. Research issues include the following: What is the nature of the microbial flora that develop? How does it respond dynamically to perturbation in inputs (gas, solid, and liquid stream) and temperature? How does it respond to alterations in design variables (e.g., mean solids, retention time, hydraulic residence time, temperature, and waste input mix)? Does phosphorus control the rate of nitrogen mineralization? What are the elemental interactions that limit the rate of decomposition? What are the possibilities for physiochemical or biological control? What are the pathogens (this may be a key to determining the reliability and controllability of the process)? What are the interfaces? Implied in this is the development of computer simulations approximating the dynamic responses in such systems.

3. How are refractory compounds to be handled? Are the levels high enough to produce problems in plant growth upon continuous recycle? If these compounds are harmful, can they be removed by a polishing operation (such as activated carbon)? What transformations take place in the equilization tank? If undesirable, can low-temperature storage be used to retard such reactions.

4. At less than 1 *g*, what are the problems with mixing in the bioreactor?

5. What should be done with the solid residue from the process? Options for use include a sink for material balancing (which may be necessary if food is consumed from storage), a substrate for incineration, a method for removal of heavy metals (which would be either processed separately or stored, depending on closure protocols), a possible substrate for food formation, and a traditional composting. If a food is to be produced, the bioreactor might not be optimized for oxidation but for maximizing the quantity of cell residue. What biological communities are best suited for this requirement? What sensing and control issues are raised?

6. Would an anaerobic-aerobic system be feasible or desirable? An anaerobic system would be suitable for treating highly concentrated wastes; furthermore, methane would be a by-product and could be used as a fuel for the CELSS, making the system more attractive energetically. The aerobic system

would be the polishing unit, and it could be reduced in physical size compared with that required for a simple aerobic system. The anaerobic system is more difficult to control than an aerobic system, although it might ultimately have the greatest effect (and it is more likely to produce toxic by-products). Gas cleanup problems are more significant. Anaerobic pretreatment would require a set of research questions similar to that generated for the aerobic system. Other aerobic units such as RBC (rotating biological contactor) and trickling filters should be investigated (Antonie, 1977).

Semisolid biotic oxidation (composting). Most of the issues raised with regard to aqueous biotic oxidation have direct analogs in semisolid biotic treatment. However, engineering experience with semisolid operations is much more limited than with aqueous systems.

Special additional problems related to semisolid operations are as follows:

1. How does system design affect mass and heat transfer and organism growth? How does it affect the ratios of types of organisms? What designs will give the maximum rates of decomposition? What are the maximum rates of decomposition?

2. If the decomposing residue acts as a substrate for plant growth, what are the interactions between the decomposers and plants? Are there any pathogen problems?

3. Relative humidity above the decomposition becomes a variable of interest when considering semisolid operations.

Research Priorities

Aqueous systems. The first two issues are of the greatest importance; however, issues 3 and 6 are closely related to 1 and 2. Otherwise, issues 3 through 5 are all of about equal priority. The last issue, 6, is of essentially the same priority, but solving that question involves a much greater effort. The first five research issues could be clarified to a useful level in 5 to 10 years at an average yearly expenditure of several hundred thousand dollars. This cost assumes that analytical facilities will be available at NASA as a common resource for the RLSR program. The absence of these facilities would raise the price substantially. The last area would require less time but almost as much expenditure as required for all of the other areas combined.

Semisolid systems. The order of priorities is roughly the same as for aqueous systems, except that the special problems associated with semisolid systems are as important as issues 1 and 2.

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16. Abstract

This compilation summarizes the results of two workshops held in October and December 1979, at the New England Center for Continuing Education, University of New Hampshire, Durham, New Hampshire. The purpose of the workshops was to identify particular biological issues associated with research on Controlled Ecological Life Support Systems (CELSS). The results of the workshops are intended to contribute to the development of a comprehensive program plan for the National Aeronautics and Space Administration's (NASA's) Regenerative Life Support System Research (RLSR) program.

The general processes and controls associated with two distinct experimental paradigms are examined first. Then, specific areas for research related to biotic production (food production) and biotic decomposition (waste management) are explored. These two fundamental components of the RLSR Program were examined separately at the two workshops. Issues of human nutrition, environmental requirements, and overall system management were not considered in these sessions.

The workshop discussions were directed toward elemental cycles and the biological factors that affect the transformations of nutrients into food, of food material into waste, and of waste into nutrients. To focus on biological issues, the discussion assumed that (1) food production would be by biological means (thus excluding chemical synthesis), (2) energy would not be a limiting factor, and (3) engineering capacity for composition, and leak rate) would be adequate.

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